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Evaluation of oasis ecosystem risk by reliability theory in an arid area: A case study in the Shiyang River Basin, China

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Abstract

Ecosystem risk is a new concept in understanding environmental problems. It is important to study and develop quantitative methods for regional ecosystem risk analysis. In this study, some new indicators and methods for measuring oasis ecosystem risk were established using reliability theory. These indicators are linked to water resource, which is the key restricting factor in arid area oasis ecosystems. They have clear meanings and can also be compared in different arid area oases. A case study in the Liangzhou oasis of the Shiyang River Basin in China shows how to calculate these ecosystem risk indicators. The results of the case study are as follows: the reliability indicator, risk indicator, stability indicator, and integrated loss indicator of the Liangzhou oasis are 0.686, 0.314, 0.743, and 0.301, respectively. This means that the reliability degree of the oasis's ecosystem safety is 68.6%; the degree of risk that it is unsafe is 31.4%; the stability degree is 74.3%; and 30.1% of the oasis's area is supported by over-exploiting underground water and damaging the lower reaches of the ecosystem. This result can be used as a guide in controlling and managing ecosystem risk in the research area.

Key words: ecosystem risk; sustainable development; Shiyang River Basin; risk analysis

Introduction

Ecosystem risk is a common problem in our society as we pursue high economic profits. Currently, quantitative evaluation and scientific assessment of ecosystem degradation are hot topics in sustainable development research, and ecosystem risk analysis is becoming increasingly important to environmental decision-making. The goal of ecosystem risk analysis is to quantify the distribution of possible ecological effects arising from ecosystem exposure to one or more stressors, so that environmental protection efforts can be focused on strategies likely to yield the greatest reduction in ecosystem risk.

Although the concept of ecological risk assessment, which developed 20 years ago, is theoretically appealing and has been extensively discussed (Robert *et al*., 2000), analytical methodologies and research techniques on the ecosystem level are still in their infancy. The reason is obvious: ecosystems are extremely complex systems that have complex structures with sophisticated functional hierarchies. The dynamics in space and time are nonlinear and undetermined. The initial objective of ecological risk assessment is to estimate the probability that some pollutants will impact the ecosystem. Since the main focus is chemical toxins entering the ecosystem, ecological risk assessment has mostly been conducted in eco-toxicology. Most of the work has been limited to aquatic ecosystems on the microcosm scale. In the past few years, ecosystem risk assessments have been conducted on several sites using various methodologies (Cavanagh *et al*., 2000; Jooste, 2001; Jooste and Claassen, 2001; McDaniels *et al*., 1998; Oka *et al*., 2001). Scientists have coined many phrases over the years to refer to ecosystem risk assessment, including comparative risk assessment, ecological risk ranking, and multiple stressor analysis, to name just a few. All of these processes basically apply the same techniques by ranking stressors, habitats, and receptors. Objective evaluation of ecosystem risks is rare (Findly and Zheng, 1999; Xu *et al*., 2004; Li and He, 1999). Owing to different pressures on different ecosystems, developing efficient and practical assessment methods on typical ecosystem is also necessary.

An oasis is a specific ecosystem that exists within deserts in arid regions. In western China, oases are mainly distributed in the deserts and gobies. Although they take up only 4%–5% of the total area of the region, over 90% of the population and over 95% of social wealth are concentrated within the oases. The oasis is not only the most concentrated area of human activities in arid regions but also the largest area where artificial disturbances happen at the regional scale. Thus the oases, which are fragile ecosystems, play an important role in arid regions. Therefore, the study of oasis ecosystem risk is theoretically and practically essential for sustainable development in

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arid regions. Some research for arid areas has focused on driving factors for desertification, while other work has discussed the water resources' carrying capacity in an oasis (Jia and Ci, 2003; Qu, 2000; Deng, 1994; Chen, 1995; Xu, 1993, 1999; Fang, 1996). However, little has been done to address oasis ecosystem risks in Chinese arid regions. This study could serve as an example for exploring oasis ecosystem risk, their driving forces, and their impacts on the stability of the oasis. The aim of this study is to conduct a quantitative analysis for oasis land stability through water supply and water consumption based on the notion of ecosystem risk.

1 Models and risk indicators in an oasis ecosystem

An oasis is a relatively independent ecosystem in an inner river basin. The water is the determinate factor for oasis ecosystems in arid regions. Based on the balance of water supply and water consumption in an oasis, we can conduct a quantitative evaluation of an oasis ecosystem's safety and stability. With regard to ecosystem health and ecosystem stability, we construct some indicators to evaluate the risks of an oasis ecosystem.

Four indicators are formed to assess the risks in an oasis ecosystem, which are dominated by water resources: reliability indicator, risk indicator, stability indicator and integrated loss indicator.

1.1 Reliability indicator

According to reliability theory, reliability is the probability of one expected event to happen in a certain time and under certain conditions. An oasis ecosystem's reliability depends on the degree of satisfaction of water resources that feed the oasis. Thus we define the reliability indicator of an oasis ecosystem, which is determined by water resources, as the probability of the water resources of the oasis to yield a supply greater than the need. We denote it by the equation as follows:

$$\alpha = \mathrm{Prob}(X_t \in S) \tag{1}$$

Where, S is the state set that supplied water is equal to or greater than the consumed water in an oasis; X_t is a variable denoting the state of water supply at year t. When X_t is in the satisfied state, i.e. X_t belongs to S, the value of X_t is 1; otherwise, X_t is 0. Thus

$$X_t = \begin{cases} 1, & \text{when } X_t \in S \\ 0, & \text{when } X_t \notin S \end{cases} \tag{2}$$

Over a duration of n time periods, the number of times that a system is in the satisfied state is $\sum_{i=1}^{n} X_i$, so we can get α as

$$\alpha = \lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} X_i \tag{3}$$

The reliability indicator is used to evaluate the safety of an oasis ecosystem over a period of time.

1.2 Risk indicator

We define the risk indicator of an oasis' ecosystem as the probability that the supplied water resources are less than the amount needed to support the oasis. The equation is

$$r = \mathrm{Prob}(X_t \in F) \tag{4}$$

Where, F is the state set when water supply is less than needed in an oasis. We know $X_t \in F$ and $X_t \notin S$ are the same state, so $r=1-\alpha$. The reliability indicator and the risk indicator are opposite to each other. Both are defined from the point of view of probability but cannot describe the degree of loss. Therefore we must define other indicators.

1.3 Stability indicator

We define the stability indicator of an oasis ecosystem as the probability that the oasis is in the water safety state with the added condition that it was also in safety state in the previous year. The equation is:

$$\omega = \mathrm{Prob}(X_t \in S \mid X_{t-1} \in S) \tag{5}$$

Where, S has the same meaning as in the other equations. The equation shows that ω denotes the probability that the oasis' water supply is in the safety state at least two years in a row, giving us a number to evaluate the duration of the stable state of an oasis ecosystem water supply.

If we consider the probability as:

$$\beta = \mathrm{Prob}(X_t \in S \mid X_{t-1} \in F) \tag{6}$$

then β is the probability that an oasis ecosystem will return to the safety state after a year in the unsafe state. We call this the recoverability indicator of an oasis ecosystem with limited water resources.

1.4 Integrated loss indicator

The integrated loss indicator of an oasis ecosystem is denoted as

$$\chi = \sum_{i=1}^{K} p_i \rho_i \tag{7}$$

Where, K is the total number of times that the water supply has been in the unsatisfied state. p_i and ρ_i are the probability and loss degree of the i-th unsafety state, respectively. In calculation, we use the reciprocal of n (the calculated duration) as a substitute for p_i. The reason is obvious: We cannot precisely calculate the probability of water shortage every time because the data are not sufficient. ρ_i is the oasis' loss in the i-th water shortage state, so we use the damaged area divided by the total oasis area to denote this. Therefore, the integrated loss indicator shows the total loss ratio of an oasis in the calculated duration.

2 Case study and analysis

A case study is applied to the Liangzhou Oasis of the Shiyang River Basin in Northwest China. The Shiyang

River Basin is located in the east of the Hexi Corridor in Gansu Province, and it has a catchment area of 41.6×10^3 km^2. The headwaters are derived from the cold and humid to semi-arid Qilian Mountain zone from 2000 to 5000 m above sea level, and flow to a midstream temperate zone of between 1400 and 2000 m in the Liangzhou Oasis and Jinchan Oasis, and to a downstream warm temperate zone of 1000–1400 m in the Minqin Oasis (Ma *et al.*, 2005). Correspondingly, the mean annual precipitation varies markedly from 300 to 600 mm in the mountain regions to 150 to 300 mm in the Liangzhou Oasis, and to less than 100 mm in the Minqin Oasis, while the potential evaporation ranges from 700 mm in the mountains to more than 2600 mm in the desert plain. Therefore, water resources are primarily derived from precipitation and glacier meltwater in the Qilian Mountains. From east to west, there are eight tributaries: the Dajin, Gulang, Huangyang, Zamu, Jinta, Xiyin, Dongda, and Xida Rivers. The water and land resources were exploited rapidly through the population increase and the quick economic boom in the basin. Increasing utilization of water resources has also led to great temporal and spatial changes in the inter-annual water distribution and ground-water recharge across the upper, middle and lower reaches, which in turn has resulted in serious ground-water and environmental problems. The Liangzhou Oasis is in the middle reaches of the river, and 4 rivers (the Huangyang, Zamu, Jinta, and Xiyin) pass through the oasis. Owing to data limitation, we use the models built before for the Liangzhou Oasis ecosystem to give an application. The total mean surface runoff of 4 rivers and other streams in the Liangzhou Oasis is about 9.216×10^8 m^3, and the net replenished groundwater is 0.9956×10^8 m^3. Owing to low precipitation and high evaporation in the oasis, the rainwater can be ignored compared to surface runoff.

Some scientists have investigated western Chinese oasis ecosystems and obtained some useful results. Wang *et al.* (2000) found that sustaining one-hectare oasis of land requires 5420 m^3 of water resources. According to Chen's (1995) research, the average vegetation water use is about 4000 m^3/hm^2 in the Shiyang River Basin. We also get a linear regression between oases areas (x, 10^4 hm^2) and water resources (y, 10^8 m^3) using 14 counties' data in the Hexi Corridor: $y = 0.4525x$ (R^2=0.9939). This means the average vegetation water use is 4525 m^3/hm^2. Considering that over-exploitation of groundwater exists at large in the region, and life water use and industry water use are not included in vegetation water use, we use the figure 5420 m^3/hm^2. Xu *et al.* (2003) also supportet this result. The area of the Liangzhou Oasis is 173300 hm^2; therefore, sustaining the oasis ecosystem requires 9.383×10^8 m^3 of water resources. The data are the water resources datum mark to ensure the oasis ecosystem safety.

Based on 51 years of annual data from 1950 to 2000, we calculated the usable water resource annually (Table 1, column 2). The safety states for every year were calculated for comparing usable water resources and datum mark. If it is in the safety state, we assign it as 1; otherwise, assign it as 0 (Table 1, column 3). To calculate the integrated loss indicator, we compute the damaged area and loss ratio in the unsafe state (Table 1, columns 4 and 5). Here, the usable water resource is the surface runoff plus groundwater and mines runoff which is divided to lower reach (calculated according to water division plan). The damage area is the part of the oasis area that did not have water to sustain it, but it was sustained by overly exploiting groundwater. The loss ratio is the percentage of lost area in the total oasis area.

According to the models in Section 1, Eqs. (1)–(7), ecosystem risk indicators in the Liangzhou Oasis are: reliability indicator, α=0.686; risk indicator, r=0.314; stability indicator, ω=0.743; recoverability indicator, β=0.500; and integrated loss indicator, χ=0.301.

These results show that the water-decided ecosystem reliability indicator of the oasis is 0.686. This means that to support the 173300 hm^2 Liangzhou Oasis, the water resources' reliability is 68.6% under the condition of the water division plan (divided 1.7×10^8 m^3 runoff in the 4 rivers to Minqin Oasis) and reasonable groundwater exploitation. This result is calculated through the last 51 years' history record, so it should be credible.

The risk indicator r=0.314 shows that there is a 31.4% chance that the water resources will not be enough to sustain the oasis area, i.e. nearly 1/3 of the years are water shortage years. Thus different departments compete to exploit water resources in the oasis. The groundwater was extremely exploited and ecological water was reduced during these years. This also increased the water shortage risk in lower reach area.

The recoverability indicator β=0.500 shows that the probability that the oasis ecosystem will recover from the water resources unsafe state to the water resource safe state is 50%. This means that the time that the oasis ecosystem is in the unsafe state is long, and it is difficult to recover to the safe state.

The stability indicator ω=0.743 shows that the probability for an oasis to be in the water safety state two years in a row is 74.3%. This value is quite close to the assuring ratio of agricultural irrigation of the oasis, 75%. Therefore, the result is reasonable.

The integrated loss indicator χ=0.301 shows that 30.1% of the oasis ecosystem is damaged by water shortage in the oasis. Although these areas did not actually become desert, they depended on the exploitation of underground water, thus damaging the lower reaches of the ecosystem. In the oasis' sustainable development view, the damage is irreversible.

3 Discussion

The evaluation of oasis ecosystem risk is a great task; either the workload will be too heavy, or the results will be too difficult to comprehend if you want to cover every aspect of the matter. In some situations, owing to the use of inappropriate methods or using even a little bit of inaccurate data, the evaluated result will be fallible. Therefore, it is essential to determine the key factors for evaluating ecosystem risk. This way the results are easy to explain.

Table 1 Usable water resources and calculated results of ecological safety in the Liangzhou Oasis

Year	Usable water resources[a] ($10^8 m^3$)	Mark of safety state	Damaged area (hm^2)	Loss ratio (%)	Year	Usable water resources[a] ($10^8 m^3$)	Mark of safety state	Damaged area (hm^2)	Loss ratio (%)
1950	12.309	1			1975	10.189	1		
1951	11.643	1			1976	11.261	1		
1952	13.584	1			1977	11.198	1		
1953	12.998	1			1978	9.752	1		
1954	14.464	1			1979	10.43	1		
1955	13.51	1			1980	9.7895	1		
1956	11.598	1			1981	10.9658	1		
1957	10.598	1			1982	9.246	0	2528	1.459
1958	16.26	1			1983	11.414	1		
1959	12.555	1			1984	9.8285	1		
1960	10.179	1			1985	9.7772	1		
1961	13.13	1			1986	9.9692	1		
1962	8.196	0	21900	12.64	1987	9.0774	0	5638	3.254
1963	8.906	0	8801	5.078	1988	12.6821	1		
1964	12.689	1			1989	13.4125	1		
1965	7.642	0	32122	18.54	1990	10.6925	1		
1966	8.627	0	13948	8.05	1991	7.235	0	39631	22.868
1967	13.759	1			1992	9.34	0	793	0.458
1968	10.278	1			1993	11.375	1		
1969	10.294	1			1994	9.342	0	756	0.437
1970	11.605	1			1995	9.268	0	2122	1.224
1971	9.991	1			1996	9.132	0	4631	2.67
1972	9.282	0	1863	1.075	1997	9.282	0	1863	1.075
1973	10.505	1			1998	9.1	0	5221	3.0
1974	9.263	0	2214	1.278	1999	8.163	0	22509	12.99
					2000	10.150	1		

[a] The usable water resource is the surface runoff (4 rivers (Huangyang, Zamu, Jinta, Xiyin) runoff and mountain area streams runoff) plus exploitable groundwater, and mine runoff which is divided to lower reach (according to water division plan, it is about 1.7×10^8 m^3). The original data from the Water Conservancy Bureau of Wuwei. 1: safe; 0: unsafe.

Oasis ecosystem risk assessment can be done through other methods based on specific stresses and special goals, but water resource is the key factor. Selecting water resource shortage as stress and oasis area as endpoint, we conducted a risk assessment of the Liangzhou Oasis in this study. Water is the dominating factor of oasis ecosystem in arid regions, so the research is rational.

The innovation of methodology is important in scientific research. Using the ideas of ecosystem safety and ecosystem stability, a few ecosystem risk indicators are established. Based on the particularity of oasis ecosystem, we get the relationship of oasis area and water resources. Using reliability theory in ecosystem assessment research, we successfully conducted an ecosystem risk assessment in the Liangzhou Oasis.

The risk of oasis ecosystem is tightly correlated to oasis water resources. The main risk of an arid oasis ecosystem stems from uncertainty of water resources, and the area of an oasis is a function of water resources (Jia and Ci, 2003; Chen, 1995; Tang, 1995). Getting water resources as risk source, based on the relationship of water and oasis area, we can evaluate ecosystem risk in different oases. The results in different oases can be compared.

The indicators we established have explicit meaning. These indicators are established through probability function, and can be easily understood in ecology. For example, reliability indicator actually denotes the historical probability of water resources being sufficient to sustain an oasis ecosystem.

Oasis ecosystem stability and ecosystem health can use the same idea for quantitative evaluation. Ecosystem stability and ecosystem health are very important concepts in up-to-date ecology, but it is difficult to quantify research. The indicators we established in the paper can be borrowed to use in these fields for oasis ecosystem evaluation in arid regions. Therefore, this research gives useful ideas for the measurable study of ecosystems.

The case study of the Liangzhou Oasis ecosystem in the Shiyang River Basin gives us some useful results. The risk indicator 0.314 shows that the oasis ecosystem faces relatively large risks. The reliability indicator 0.686 shows the oasis security is low. The recoverability indicator 0.500 implies that the probability of the oasis's recovering to the safe state is low when it is in the unsafe state, only 50%. The stability indicator 0.743 means the assuring ratio of water resources in the oasis ecosystem is 74.3%. The integrated loss indicator 0.301 means the accumulative ecological damage is serious. Accumulative damage area is 30.1% of the total oasis area because of the uncertainty of water resources. The results can be used as a guide for ecosystem risk management and risk control in the research region.

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